SUSPENSION SYSTEM FOR A VEHICLE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present invention is a continuation-in-part of International Application No. PCT/US01/48488, filed 07 December 2001 and entitled "Suspension System For A Vehicle", which claims benefit of U.S. provisional application Serial No. 60/251,951, filed 07 December 2000 and entitled "Compressible Fluid Strut".

TECHNICAL FIELD

[0002] The subject matter of this invention generally relates to suspension systems for a vehicle and, more particularly, to suspension systems including a compressible fluid.

BACKGROUND

[0003] In the typical vehicle, a combination of a coil spring and a gas strut function to allow compression movement of a wheel toward the vehicle and rebound movement of the wheel toward the ground. The suspension struts attempt to provide isolation of the vehicle from the roughness of the road and resistance to the roll of the vehicle during a turn. More specifically, the typical coil spring provides a suspending spring force that biases the wheel toward the ground and the typical gas strut provides a damping force that dampens both the suspending spring force and any impact force imparted by the road. Inherent in every conventional suspension

strut is a compromise between ride (the ability to isolate the vehicle from the road surface) and handling (the ability to resist roll of the vehicle). Vehicles are typically engineered for maximum road isolation (found in the luxury market) or for maximum roll resistance (found in the sport car market). There is a need, however, for an improved suspension system that avoids this inherent compromise.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIGURE 1 is a cut away perspective view of the suspension system of the preferred embodiment, shown within a vehicle.

[0005] FIGURE 2 is a schematic view of the suspension system of FIGURE 1.

[0006] FIGURE 3 is a cross-sectional view of a suspension strut of the suspension system of FIGURE 1.

[0007] FIGURE 4 is a detailed view of the volume modulator of the suspension system of FIGURE 1.

[0008] FIGURES 5A, 5B, 6A, and 6B are schematic views of the different stages of the volume modulator of FIGURE 4.

[0009] FIGURE 7 is a schematic view of the volume modulator of a second preferred embodiment.

[0010] FIGURE 8A, 8B, 9A, and 9B are schematic views of the different stages of the volume modulator of FIGURE 7.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0011] The following description of the preferred embodiments of the invention is not intended to limit the invention to these preferred embodiments, but rather to enable any person skilled in the art of suspension systems to use this invention.

[0012] As shown in FIGURE 1, the suspension system 10 of the preferred embodiment includes a compressible fluid 12, a suspension strut 14, a hydraulic cavity 16, a reservoir 18, and a volume modulator 20. The hydraulic cavity 16, which is at least partially defined by the suspension strut 14, contains a portion of the compressible fluid 12 and cooperates with the compressible fluid 12 to supply a suspending spring force. The suspending spring force biases a wheel 22 of the vehicle 24 toward the surface. The volume modulator 20, which is coupled to the hydraulic cavity 16 and to the reservoir 18, selectively pushes the compressible fluid 12 from the reservoir 18 into the hydraulic cavity 16 and vents the compressible fluid 12 from the hydraulic cavity 16 into the reservoir 18, thereby actively modulating the suspending spring force. By increasing the suspending spring force in the suspension struts 14 of the outside wheels during a turn, the vehicle 24 can better resist roll. By decreasing the suspending spring force over rough surfaces, the vehicle 24 can better isolate the passengers. Thus, by actively modulating the suspending spring force, the vehicle 24 can maximize both ride and handling and avoid the inherent compromise of conventional suspension systems.

[0013] As shown in FIGURES 1 and 2, the suspension system 10 of the preferred embodiment has been specifically designed for a vehicle 24 having four wheels 22 and four suspension links 26 (two shown in FIGURE 2) suspending the individual wheels 22 from the vehicle 24. The suspension links 26 allow

compression movement of the individual wheels 22 toward the vehicle 24 and rebound movement of the individual wheels toward the road surface. Despite this design for a particular environment, the suspension system 10 may be used in any suitable environment, such as other vehicles with more or less wheels.

[0014] The compressible fluid 12 of the preferred embodiment, which cooperates to supply the suspending spring force, is preferably a silicon fluid that compresses about 1.5% volume at 2,000 psi, about 3% volume at 5,000 psi, and about 6% volume at 10,000 psi. Above 2,000 psi, the compressible fluid has a larger compressibility than conventional hydraulic oil. The compressible fluid, however, may alternatively be any suitable fluid, with or without a silicon component, that provides a larger compressibility above 2,000 psi than conventional hydraulic oil.

[0015] As shown in FIGURES 2 and 3, the suspension strut 14 of the preferred embodiment includes a hydraulic tube 28, a displacement rod 30, a cavity piston 32, a first variable restrictor 34, and a second variable restrictor 36. The hydraulic tube 28 and displacement rod 30 of the preferred embodiment cooperatively function to couple the suspension link and the vehicle and to allow compression movement of the wheel 22 toward the vehicle and rebound movement of the wheel 22 toward the road surface. The hydraulic tube 28 preferably defines an inner cavity 38, which functions to contain a portion of the compressible fluid 12. As previously mentioned, the inner cavity 38 and the compressible fluid 12 preferably cooperate to supply the suspending spring force that biases the wheel 22 toward the surface and, essentially, suspend the entire vehicle above the surface. The displacement rod 30 is adapted to move into the inner cavity 38 upon the

compression movement of the wheel 22 and to move out of the inner cavity 38 upon the rebound movement of the wheel 22. As it moves into the inner cavity 38, the displacement rod 30 displaces, and thereby compresses, the compressible fluid 12. In this manner, the movement of the displacement rod 30 into the inner cavity 38 increases the suspending spring force of the suspension strut 14. As the displacement rod 30 moves out of the inner cavity 38, the compressible fluid 12 decompresses and the suspending spring force of the suspension strut 14 decreases. The displacement rod 30 is preferably cylindrically shaped and, because of this preference, the displacement of the displacement rod 30 within the inner cavity 38 and the magnitude of the suspending spring force have a linear relationship. If a linear relationship is not preferred for the particular application of the suspension strut 14, or if there is any other appropriate reason, the displacement rod 30 may be alternatively designed with another suitable shape. The hydraulic tube 28 and the displacement rod 30 are preferably made from conventional steel and with conventional methods, but may alternatively be made from any suitable material and with any suitable method.

[0016] The cavity piston 32 of the preferred embodiment is preferably coupled to the displacement rod 30 and preferably extends to the hydraulic tube 28. In this manner, the cavity piston 32 separates the inner cavity 38 into a first section 40 and a second section 42. The cavity piston 32 defines a first orifice 44 and a second orifice 46, which both preferably extend between the first section 40 and the second section 42 of the inner cavity 38. The first orifice 44 and the second orifice 46 function to allow flow of the compressible fluid 12 between the first section 40 and the second section 42 of the inner cavity 38. The cavity piston 32 is preferably

securely mounted to the displacement rod 30 by a conventional fastener 48, but may alternatively be integrally formed with the displacement rod 30 or securely mounted with any suitable device. The cavity piston 32 is preferably made from conventional materials and with conventional methods, but may alternatively be made from other suitable materials and with other suitable methods.

[0017] The first variable restrictor 34 of the preferred embodiment is coupled to the cavity piston 32 near the first orifice 44. The first variable restrictor 34 functions to restrict the passage of the compressible fluid 12 through the first orifice 44 and, more specifically, functions to variably restrict the passage based on the velocity of the cavity piston 32 relative to the hydraulic tube 28. In the first preferred embodiment, the first variable restrictor 34 is a first shim stack 50 preferably made from conventional materials and with conventional methods. In alternative embodiments, the first variable restrictor 34 may include any other suitable device able to variably restrict the passage of the compressible fluid 12 through the first orifice 44 based on the velocity of the cavity piston 32 relative to the hydraulic tube 28. The second variable restrictor 36 of the preferred embodiment is coupled to the cavity piston 32 near the second orifice 46. The second variable restrictor 36 - like the first variable restrictor 34 - functions to restrict the passage of the compressible fluid 12 through the second orifice 46 and, more specifically, functions to variably restrict the passage based on the velocity of the cavity piston 32 relative to the hydraulic tube 28. In the preferred embodiment, the second variable restrictor 36 is a second shim stack 52 preferably made from conventional materials and with conventional methods. In alternative embodiments, the second variable restrictor 36 may include any suitable device able to variably restrict a passage of the

compressible fluid 12 through the second orifice 46 based on the velocity of the cavity piston 32 relative to the hydraulic tube 28.

[0018] The cavity piston 32, the first orifice 44, and the first variable restrictor 34 of the preferred embodiment cooperate to supply the rebound damping force during the rebound movement of the wheel 22. The rebound damping force acts to dampen the suspending spring force that tends to push the displacement rod 30 out of the hydraulic tube 28. The cavity piston 32, the second orifice 46, and a second variable restrictor 36, on the other hand, cooperate to supply the compression damping force during the compression movement of the wheel 22. The compression damping force acts to dampen any impact force that tends to push the displacement rod 30 into the hydraulic tube 28.

[0019] The suspension strut 14 of the preferred embodiment is further described in U.S. application filed on 07 December 2001, entitled "Compressible Fluid Strut", and assigned to Visteon Global Technologies, Inc. As described in that application, the suspension strut may include a pressure vessel and may include a valve. In alternative embodiments, the suspension strut may include any suitable device to allow active modulation of the suspending spring force with compressible fluid.

[0020] As shown in FIGURE 1, the suspension system 10 of the preferred embodiment also includes hydraulic lines 54 adapted to communicate the compressible fluid 12 between the individual suspension struts 14 and the volume modulator 20. Together with the inner cavity 38 of the individual suspension struts 14, the hydraulic lines 54 define individual hydraulic cavities 16. Preferably, the compressible fluid 12 flows freely between the volume modulator 20 and the inner

cavity 38 of the individual suspension struts 14. Alternatively, the hydraulic cavities 16 may include one or more controllable valves such that the hydraulic cavity 16 is entirely defined by the suspension strut 14 or by the suspension strut 14 and a portion of the hydraulic line 54.

[0021] As shown in FIGURE 2, the reservoir 18 functions to contain a portion of the compressible fluid 12 that has been vented from the hydraulic cavity 16 and that may eventually be pushed into the hydraulic cavity 16. The reservoir 18 is preferably made from conventional materials and with conventional methods, but may alternatively be made from any suitable material and with any suitable method. The suspension system 10 of the preferred embodiment includes a pump 56 adapted to pressurize the compressible fluid 12 within the reservoir 18. In this manner, the reservoir 18 acts as an accumulator 58. By using compressible fluid 12 under a pressure of about 1500 psi within the reservoir 18, the volume modulator 20 consumes less energy to reach a particular pressure within an individual hydraulic cavity 16. In an alternative embodiment, the compressible fluid 12 within the reservoir 18 may be at atmospheric pressure or may be vented to the atmosphere.

[0022] As shown in FIGURE 2, the volume modulator 20 is coupled to the hydraulic line 54 and to the reservoir 18. The volume modulator 20, as previously mentioned, functions to selectively push the compressible fluid 12 into the hydraulic cavity 16 and to vent the compressible fluid 12 from the hydraulic cavity 16. In the preferred embodiment, the volume modulator 20 is a digital displacement pump/motor as described in U.S. Patent No. 5,259,738 entitled "Fluid-Working Machine" and issued to Salter et al. on 09 November 1993, which is incorporated in its entirety by this reference. In alternative embodiments, the volume modulator 20

may be any suitable device that selectively pushes the compressible fluid 12 into the hydraulic cavity 16 and vents the compressible fluid 12 from the hydraulic cavity 16 at a sufficient rate to actively modulate the suspending spring force.

[0023] As shown in FIGURE 4, the volume modulator 20 of the preferred embodiment defines a modulator cavity 60 and includes a modulator piston 62 adapted to continuously cycle through a compression stroke and an expansion stroke within the modulator cavity 60. The modulator piston 62 is preferably connected to an eccentric 64 that is rotated by a motor 66 (shown in FIGURE 1). Because of the "active" nature of the modulation of the suspending spring force, the modulator piston 62 cycles through the compression stroke and expansion stroke at a relatively high frequency (up to 30 Hz) and, thus, the motor preferably rotates at a relatively high rotational velocity (up to 2000 rpm).

[0024] The volume modulator 20 of the preferred embodiment also includes a valve system 67, which includes a cavity-side valve 68 coupled between the hydraulic line and the volume modulator 20 and a reservoir-side valve 70 coupled between the reservoir and the volume modulator 20. The cavity-side valve 68 and the reservoir-side valve 70 function to selectively restrict the passage of the compressible fluid. Preferably, the cavity-side valve 68 and the reservoir-side valve 70 are so-called poppet valves that may be actuated at relatively high frequencies. Alternatively, the cavity-side valve 68 and the reservoir-side valve 70 may be any suitable device that selectively restricts the passage of the compressible fluid at an adequate frequency.

[0025] As shown in FIGURES 5A and 5B, the cavity-side valve 68, the reservoir-side valve 70, and the modulator piston 62 can cooperate to draw

compressible fluid 12 from the reservoir and push the compressible fluid 12 into the hydraulic cavity. In the first stage, as shown in FIGURE 5A, the cavity-side valve 68 is closed and the reservoir-side valve 70 is opened, while the modulator piston 62 increases the volume in the modulator cavity 60 (the expansion stroke). The expansion stroke of the modulator piston 62 draws the compressible fluid 12 into the modulator cavity 60. During the second stage, as shown in FIGURE 5B, the reservoir-side valve 70 is closed and the cavity-side valve 68 is opened, while the modulator piston 62 decreases the volume in the modulator cavity 60 (the compression stroke). The compression stroke of the modulator piston 62 pushes the compressible fluid 12 into the hydraulic cavity, which increases the suspending spring force at that particular suspension strut and wheel.

[0026] As shown in FIGURES 6A and 6B, the cavity-side valve 68, the reservoir-side valve 70, and the modulator piston 62 can also cooperate to draw compressible fluid 12 from the hydraulic cavity and vent the compressible fluid 12 into the reservoir. In the first stage, as shown in FIGURE 6A, the cavity-side valve 68 is opened and the reservoir-side valve 70 is closed, while the modulator piston 62 increases the volume in the modulator cavity 60 and draws the compressible fluid 12 into the modulator cavity 60. During the second stage, as shown in FIGURE 6B, the reservoir-side valve 70 is opened and the cavity-side valve 68 is closed, while the modulator piston 62 decreases the volume in the modulator cavity 60 and vents the compressible fluid 12 into the reservoir, which decreases the suspending spring force at that particular suspension strut and wheel.

[0027] During the operation of the vehicle, it may be advantageous to neither increase nor decrease the suspending spring force. Since the motor 66, the

eccentric 64, and the modulator pistons 62 are continuously moving, the reservoir-side valve 70 and the volume modulator 20 can also cooperate to draw compressible fluid 12 from the reservoir (shown in FIGURE 5A) and vent the compressible fluid 12 back into the reservoir (shown in FIGURE 6B). This process does not modulate the pressure of the hydraulic cavity 16 and does not increase or decrease the suspending spring force.

[0028] Although FIGURES 5A, 5B, 6A, and 6B show only one modulator cavity 60 and modulator piston 62, the volume modulator 20 preferably includes a modulator cavity 60, a modulator piston 62, a cavity-side valve 68, and a reservoir-side valve 70 for each suspension strut 14 on the vehicle 24. Preferably, the motor 66 and the eccentric 64 drive the multiple modulator pistons 62, but the individual modulator pistons 62 may alternatively be driven by individual motors and individual eccentrics. Further, a control unit 72 (shown in FIGURE 1) may individually control the cavity-side valve 68 and reservoir-side valve 70 corresponding to a particular suspension strut 14 and wheel 22 to adjust the ride and handling of the vehicle 24 on a wheel-to-wheel basis. The control unit 72 may also be used to adjust particular suspension struts 14 on a side-by-side basis of the vehicle 24 to adjust the roll or the pitch of the vehicle 24. The control unit 72 may further be used to adjust all of the suspension struts 14 to adjust the ride height of the vehicle 24. The control unit 72 is preferably made from conventional material and with conventional methods, but may alternatively be made from any suitable material and with any suitable method.

[0029] As shown in FIGURE 7, the volume modulator 120 of the second preferred embodiment shares many components with the volume modulator 20 of the first preferred embodiment, including a modulator cavity 60, a modulator piston

62, an eccentric 64, a motor 66 (shown in FIGURE 1), and a valve system 167. Like the valve system 67 of the first preferred embodiment, the valve system 167 of the second preferred embodiment functions to selectively restrict the passage of the compressible fluid between the hydraulic cavity and the modulator cavity 60 or restrict the passage of the compressible fluid between the reservoir and the modulator cavity 60. The valve system 167 of the second preferred embodiment, however, includes a rotary valve 174 coupled between the modulator cavity 60, the hydraulic cavity, and the reservoir.

[0030] As shown in FIGURE 8A, the rotary valve 174 of the second preferred embodiment is adapted to selectively rotate to a first position thereby restricting the passage of the compressible fluid between the hydraulic cavity and the modulator cavity 60 and allowing the passage of the compressible fluid between the reservoir and the modulator cavity 60. As shown in FIGURE 8B, the rotary valve 174 is further adapted to selectively rotate to a second position thereby restricting the passage of the compressible fluid between the reservoir and the modulator cavity 60 and allowing the passage of the compressible fluid between the hydraulic cavity and the modulator cavity 60.

[0031] As shown in FIGURES 8A and 8B, the rotary valve 174 and the modulator piston 62 can cooperate to draw compressible fluid 12 from the reservoir and push the compressible fluid 12 into the hydraulic cavity. In the first stage, as shown in FIGURE 8A, the rotary valve 174 is rotated into the first position, while the modulator piston 62 increases the volume in the modulator cavity 60 (the expansion stroke). The expansion stroke of the modulator piston 62 draws the compressible fluid 12 into the modulator cavity 60. During the second stage, as shown in FIGURE

8B, the rotary valve 174 is rotated into the second position, while the modulator piston 62 decreases the volume in the modulator cavity 60 (the compression stroke). The compression stroke of the modulator piston 62 pushes the compressible fluid 12 into the hydraulic cavity, which increases the suspending spring force at that particular suspension strut and wheel.

[0032] As shown in FIGURES 9A and 9B, the rotary valve 174 and the modulator piston 62 can also cooperate to draw compressible fluid 12 from the hydraulic cavity and vent the compressible fluid 12 into the reservoir. In the first stage, as shown in FIGURE 9A, the rotary valve 174 is rotated into the second position, while the modulator piston 62 increases the volume in the modulator cavity 60 and draws the compressible fluid 12 into the modulator cavity 60. During the second stage, as shown in FIGURE 9B, the rotary valve 174 is rotated into the first position, while the modulator piston 62 decreases the volume in the modulator cavity 60 and vents the compressible fluid 12 into the reservoir, which decreases the suspending spring force at that particular suspension strut and wheel.

[0033] As mentioned above, during the operation of the vehicle, it may be advantageous to neither increase nor decrease the suspending spring force. Since the motor 66, the eccentric 64, and the modulator pistons 62 are continuously moving, the rotary valve 174 and the volume modulator 20 can also cooperate to draw compressible fluid 12 from the reservoir (shown in FIGURE 8A) and vent the compressible fluid 12 back into the reservoir (shown in FIGURE 9B). This process does not modulate the pressure of the hydraulic cavity and does not increase or decrease the suspending spring force.

[0034] As shown in FIGURE 7, the valve system 167 of the second preferred embodiment also includes a hydraulic cavity valve 176 coupled along the hydraulic cavity between the volume modulator 120 and the suspension strut. The hydraulic cavity valve 176 functions to selectively restrict the passage of the compressible fluid through the hydraulic cavity during an "off" condition of the suspension system, while selectively allowing the passage of the compressible fluid through the hydraulic cavity during an "on" condition of the suspension system, as shown in FIGURES 8A, 8B, 9A, and 9B. Preferably, the hydraulic cavity valve 176 is a so-called poppet valve with sufficient sealing properties. Alternatively, the hydraulic cavity valve 176 may be any suitable device that selectively restricts the passage of the compressible fluid during the "off" condition of the suspension system. When using the valve system 167 with the hydraulic cavity valve 176, the sealing requirements of the rotary valve 174 are reduced.

[0035] Although FIGURES 8A, 8B, 9A, and 9B show only one modulator cavity 60 and modulator piston 62, the volume modulator 120 preferably includes at least one modulator cavity 60, a modulator piston 62, and a valve system 167 with a rotary valve 174 for each suspension strut 14 on the vehicle 24. The control unit 72 (shown in FIGURE 1) may individually control the rotary valve 174 corresponding to a particular suspension strut 14 and wheel 22 to adjust the ride and handling of the vehicle 24 on a wheel-to-wheel basis. The control unit 72 may also be used to adjust particular suspension struts 14 on a side-by-side basis of the vehicle 24 to adjust the roll or the pitch of the vehicle 24. The control unit 72 may further be used to adjust all of the suspension struts 14 to adjust the ride height of the vehicle 24.

[0036] As any person skilled in the art of suspension systems will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the preferred embodiment of the invention without departing from the scope of this invention defined in the following claims.